High Frequency Acoustic Reflection and Transmission in Ocean Sediments

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LONG-TERM GOALS

Development of a physical model of high-frequency acoustic interaction with the ocean floor, including penetration through and reflection from smooth and rough water/sediment interfaces, scattering from the interface roughness and volume heterogeneities and propagation within the sediment. The model will aid in the detection and classification of buried mines and improve SONAR performance in shallow water.

OBJECTIVES

1) New finite element modeling capability for acoustic sediment interactions.
2) A comparative study of acoustic sediment interaction models including visco-elastic, Biot, BICSQS, and grain shearing and scattering models including perturbation theory, small slope approximation and finite element models through careful comparison with experimental measurements of the bistatic return, for the purpose of defining the best physical model of high-frequency acoustic interaction with the ocean floor.
3) An inversion methodology that can provide input parameters for the resulting physical model from reflection coefficient measurements.

APPROACH

Our approach to this problem has three distinct areas of concentration: 1) Development of a finite element model of scattering from rough interfaces in a shallow water waveguide, 2) Development of a fully three dimensional finite element scattering model and 3) Improving the methodology for the inversion of reflection coefficient data to overcome the effects of propagation and scattering.

WORK COMPLETED

The main achievements of 2009 include:

1) Development of a finite element reverberation model for shallow water waveguides.

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2) Preliminary three-dimensional finite element rough bottom scattering model.

3) Development of an algorithm for the classification of sediments through reflection coefficient measurements

Finite Element Propagation Modeling.

ARL:UT has developed a two dimensional finite element model to serve as a benchmark for propagation in shallow water waveguide with rough boundaries. The five modeled environments were based on the problems of the ONR Reverberation workshop. Each of the waveguides was two-dimensional with a line source at 15 m depth and a receiver, mono-static in range, at 25 m depth in a 50 m water column over a medium sand half space. The source frequency was centered at 250 Hz. The five waveguides varied in the roughness of the interfaces and the sound speed profile. These are summarized in Table 1. The roughness for both the sediment interface and the air/water interface was provided by the workshop.

Table 1: Waveguides Calculated using FEM

Problem	Water sound speed profile	Water/sediment interface	Air/water interface
Control	Iso-velocity	Flat	Flat
1	Iso-velocity	Rough	Flat
2	Iso-velocity	Flat	Rough
3	Iso-velocity	Rough	Rough
4	Summer Profile Sound Speed at 0 m depth: 1515 m/s Gradient: -0.3 m/s/m	Rough	Rough
5	Winter Profile Sound Speed at 0 m depth: 1495 m/s Gradient: 0.1 m/s/m	Rough	Rough

Time harmonic solutions were calculated using a commercial finite element software, COMSOL. The domain was truncated using perfectly matched layers. [Berenger, 1996.] The Fourier synthesis method was used in order to construct a reverberation time series. The solution was convolved with the provided source spectrum. An example of the time domain solution for a short waveguide with rough boundaries is shown in Fig. 1. In this solution, the impulse response for the band from 210 to 290 Hz is shown in order to separate the returns. Note how the fathometer returns are very distinct near the source and receiver at zero range. Also, effects of scattering especially near the air/water interface are evident.

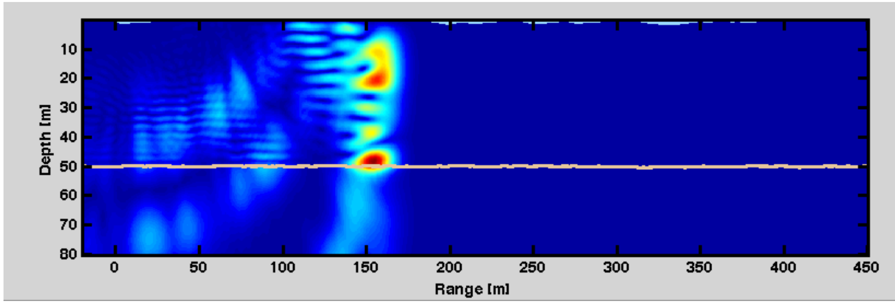


Figure 1: FEM time domain solution for a short waveguide with rough boundaries.

Additionally, the finite element method was used to calculate the transmission loss from a waveguide with an elastic bottom. In this case, the effects of a thin sediment layer were quantified by calculating a 42 m deep waveguide over a calcarenite bottom with and without a overlying sand layer. The environment was taken from an experimental study. [Fan, 2009.]

The reflection coefficient as a function of angle is given for the calcarenite with varying depths of overlying sand in Fig. 2. Because of the large difference in reflection coefficient for the sand layer and the overlying sediment, particularly at small grazing angles, the sandy layer has a significant effect on the transmission loss at large ranges.

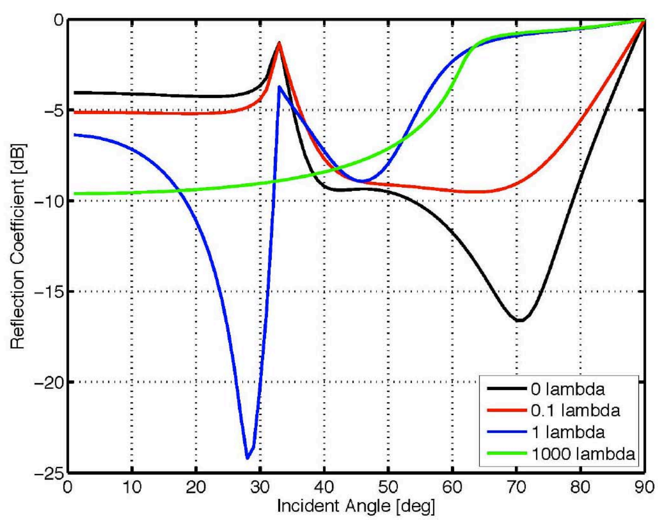


Figure 2: The reflection coefficient for calcarenite with overlying sandy sediment with varying layer depths relative to an acoustic wavelength.

Three Dimensional Scattering Model

In addition to two dimensional propagation, finite elements are being used to investigate scattering in three dimensions. In this work, a two dimensional roughness is created from a given wavenumber spectrum. A 5 kHz Gaussian tapered plane wave is incident on the pressure release surface, and the

scattered field is calculated using FE. The field at any point from the surface can be calculated using a Green’s function approach. There is no symmetry requirement on the 2D power spectra.

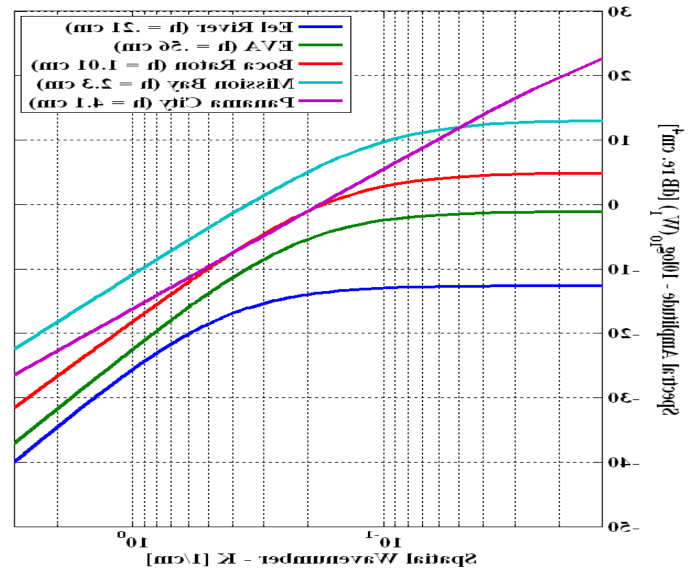


Figure 3: The power spectra used in the 3D FEM scattering analysis.

Five spectra with different RMS heights, *h*, were sampled from the literature. [Jackson, 2007.] Each spectrum was used to construct a set of 50 realizations of 2D rough surfaces. These realizations have different degrees of roughness relative to the acoustic wavelength. The power spectra are given in Fig. 3.

Reflection Coefficient Classification

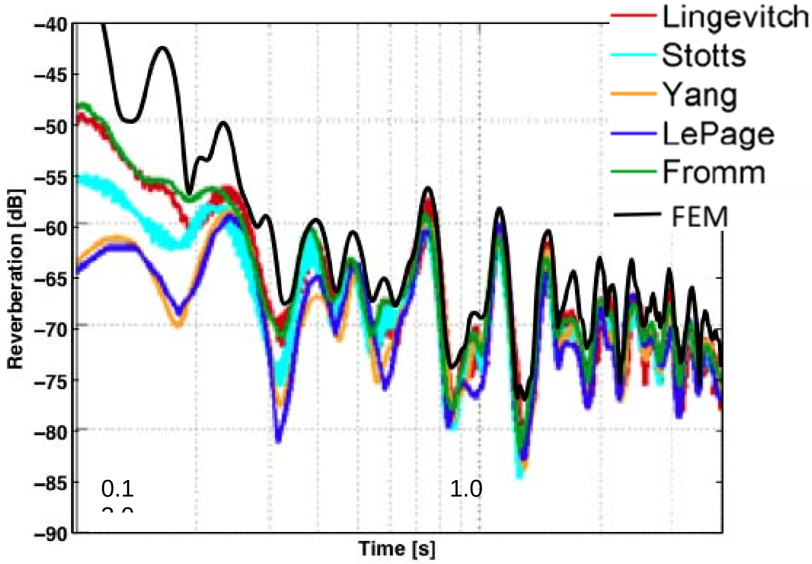
Analysis of the reflection measurements from the SAX04 sea test revealed that the data were highly variable with regards to sediment type. An algorithm was developed to bin the data in angle and frequency, parse the distributions into constituent Gaussians and then assign a sediment classification to each Gaussian distribution based on sediment models. After analysis, the sediment variability in experimental region was expressed quantitatively.

RESULTS

Finite Element Propagation Modeling.

The results of the finite element reverberation calculation were compared to the results of other published models in Fig. 4. [Thorsos, 2008.] In the figure, the curves are denoted by the investigator's last name. Stotts and Fromm used a ray based model, while Yang and LePage used a coupled mode solution. Lingevitch modeled with two-way rough bottom parabolic equations. Yang and Lingevitch averaged over 100 realizations while the other methods used a scattering model provided by the

workshop in the time domain. Overlaid on these curves is the incoherent average of 20 realizations from the FE model.



x axis is missing
Figure 4: A comparison of the finite element reverberation results and other models for Problem 1.

The finite element method predicts a reverberation that is significantly higher than that of the other models. At the earlier times (less than 0.3 seconds), this is due to the fathometer returns. Other models neglect normal and near normal incident energy, but FEM computes the total field without exception. At the later times, the difference is likely due to energy scattering from one interface to another at normal or near normal incidence, and then scattered back to the receiver. No other model considers these paths.

The reverberation from all five of the problems is plotted in Fig. 5 for an incoherent average of 20 realizations for each problem. Note how Problem 2 has a significantly lower reverberation. This is due to the normal incidence scattering from the surface transmitted into the bottom with no scattering and being removed from the waveguide. By comparing Problems 1 and 3, note also that the addition of scattering from air/water interface decreases the reverberation. Also, note also that the addition of upward or downward refracting sound speed profile has little effect on the reverberation for this frequency and geometry.

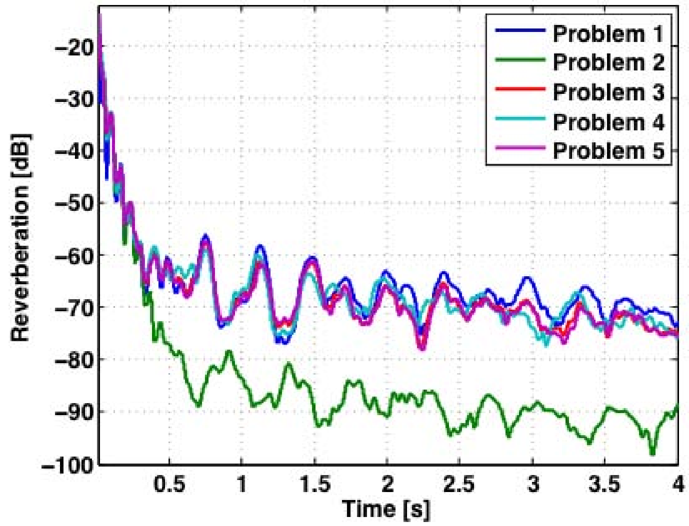


Figure 5: The reverberation plotted as a function of time for all five waveguide scenarios.

The transmission loss from a shallow water waveguide with an elastic bottom was also considered. In this case, an overlying sediment layer had a profound effect on the transmission loss. This is due to the difference in the reflection coefficients for the sediments. (See Figure 2.) As range increases, the grazing angle decreases and the layer thickness appears larger relative to the normal component of the acoustic wavelength. Therefore, at longer ranges, transmission loss is primarily influenced by the sand layer. Adding interface roughness, in this case to all three boundaries, air/water, water/sand and sand/calcarenite, increases the energy loss at longer ranges.

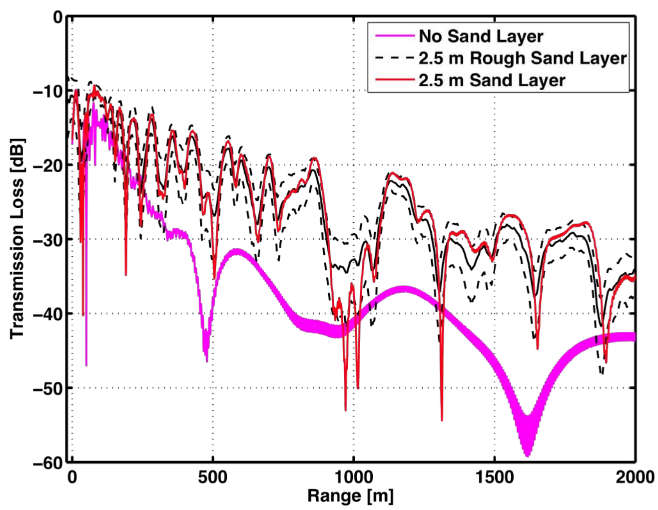


Figure 6: The transmission loss in a shallow water waveguide with a calcarenite bottom as a function of range with and without a sediment layer. The solid black line indicates the rough interface transmission loss mean. One standard deviation from the mean is plotted with a dashed line.

Three Dimensional Scattering Model

The scattering of a Gaussian tapered plane wave from a rough interface was calculated using finite elements for both a fully three dimensional model and a two dimensional slice of the surface which defined the xy-plane of the 3D model. The calculated scattered pressure for the 3D model in the xy-plane and the two dimensional model are shown in Fig. 7, for a number of measured roughness spectra from previous experiments, including the Eel river, the EVA experiment off Elba Island, Boca Raton, Mission Beach, and Panama City areas.

The backscattering generally increases as the surface roughness increases in both cases. However, the computed scattering strength from the Panama City spectrum differs slightly in this regard, and it is hypothesized that this is due to the large contribution from the lower wavenumbers which may not be fully resolved in the scale of this model.

A notable difference between the 2 dimensional and 3 dimensional models is that relative to the scattering strength at specular, the backscattering strength in 2 dimensions is about 10 dB higher than that in 3. The cause of this difference is currently under investigation.

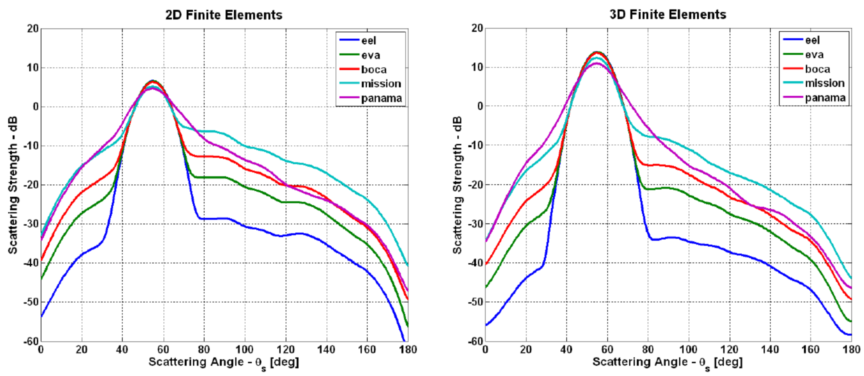


Figure 7: The scattered pressure of a Gaussian tapered plane wave on five different pressure release rough interfaces. Shown are both a two dimensional model and a three dimensional model in the xy plane.

Reflection Coefficient Classification

The binned and parsed reflection measurements from the SAX04 sea test were compared with sediment models and classified according to a least square error. The results for all of the distributions are shown in Fig. 8. The data were also separated according to the depth of the reflector relative to the nominal seafloor depth. Considering the classification in the figure, much of the data corresponds to a reflection from mud. This is especially the case for the deeper reflectors suggesting that the mud may be residing in lower lying areas. The reflections from reflectors at or near the nominal seafloor depth were mostly sand or sand layers. Lastly, reflections from above the nominal seafloor depth corresponded to gassy sediments or fish scattering particularly at higher grazing angles. This is consistent with fish swimming just above the seafloor.

The variability of the sediment was calculated by considering the classification and the amplitude of the parsed distributions. For the purposes of this calculation, the data is classified according to the overlying sediment. For the data shown in Fig. 8, 10% of the data corresponded to gassy sediments or fish, 59% of the data corresponded to mud and 31% of the data corresponded to either a half-space of sand or sand over a mud inclusion.

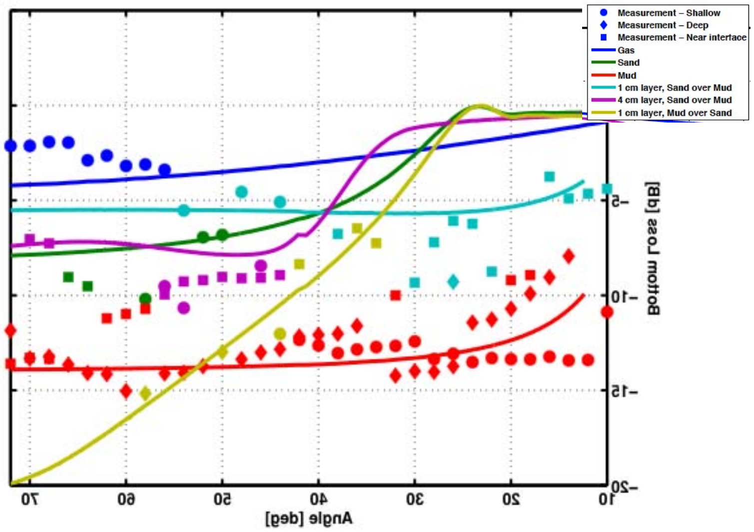


Figure 8: The high frequency reflection data from SAX04 as a function of grazing angle classified into six different types of sediments.

IMPACT/APPLICATIONS

The low frequency FE propagation model shows that there is a significant contribution to reverberation from normal or near normal incidence energy near the boundaries. This suggests a change to the current propagation models since none of the models currently accepted and certified by the Navy's Ocean Acoustic Mathematical Library (OAML) consider this effect.

TRANSITIONS

Work on sediment variability is being transitioned in the active sonar trainers via the High-Fidelity Active Sonar Training, HiFAST, project. Additionally, the quantification of scattering as a function of frequency is vital to work on the "iPUMA Sonar Environment Estimation (iSEE)" project to classify sediments from an AUV platform.

RELATED PROJECTS

This project is closely related to other projects under the ONR "High Frequency Sediment Acoustics" thrust since the environmental inputs required for analysis are dependent on other projects within the thrust. The group is an active participant in the ONR Reverberation Workshop. The work on this project is being applied to two 6.2 projects, "iPUMA Sonar Environment Estimation (iSEE)", N00014-06-G-0218 and "High-Fidelity Active Sonar Training".

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